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14. ABSTRACT
In Airborne Networks, because of the high mobility, a communications link is typically available for only a short period of time. Thus it is desirable to communicate at as high a data rate as possible to complete one’s information transfer in the available time. High data rate suggests the use of MIMO communications, multiplexing many messages over the link by using multiple antennas at each end of the link. However, communication between aircraft is usually free of scattered propagation (free space propagation), while MIMO performs best in a highly scattered environment. Nevertheless, MIMO is not necessarily ruled out in such a free space environment, providing the radio frequency is high enough, the link distance is short enough, and the antenna arrays are wide enough. We will show how nearly full data rate advantage characteristic of MIMO links can be achieved in the presence of free space propagation by means of typical examples.

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Aircraft Free-Space MIMO Wireless Communications

August 25, 2008

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PREPRINT

1. Overview

From the AF perspective, a new research and development paradigm supporting airborne networking and communications links is of paramount importance to the next-generation warfighter. In fact, to enable warfighters anywhere and everywhere to employ the same collaborative environment as they enjoy terrestrially in spite of extreme airborne and military (hostile) environments, challenges to the prevailing networking mindset must be directly confronted and overcome. Although many experts in the wired networking and communications community would like to believe that the wireless domain simply necessitates an extension of current practices and abilities, such is not the case.

Whereas the wired terrestrial realm has enjoyed the benefit of relatively high-quality, high-capacity multimedia networks and communications links over the past couple of decades, the wireless domain presents a much more formidable scenario. As compared to their wired counterparts, wireless networks currently suffer from a variety of channel impairments due to noise, other users, and co-site interference and, as such, are generally less reliable unless additional corrective measures are taken. Such challenges are further exacerbated when the transmit and/or receive platforms are mobile, especially for the AF. When traveling at Mach rates as opposed to miles-per-hour, the limited amount of fly-over time impairs synchronization and tracking and the potential impact of Doppler effects renders all but the most robust and well-designed systems impotent.

Given the dynamic, wireless environment of today's warfighter, time is of the utmost importance; new communications and networking solutions must be developed so as to ensure that mission critical information reaches its destination whenever and wherever needed. Constraints related to platform velocity, rapidly changing topologies, power, bandwidth, latency, security and covertness must all be addressed in their own right. Ultimately, solutions to such a multivariable constraint problem will have to address several of these constraints simultaneously and provide a solution that meets competing signaling objectives.

2. Introduction

In Airborne Networks, because of the high mobility, a communications link is typically available for only a short period of time. Thus it is desirable to communicate at as high a data rate as possible to complete one's information transfer in the available time. High data rate suggests the use of MIMO communications, multiplexing many messages over the link by using multiple antennas at each end of the link. However, communication between aircraft is usually free of scattered propagation (free space propagation), while MIMO performs best in a highly scattered environment. Nevertheless, MIMO is not necessarily ruled out in such a free space environment, providing the radio frequency is high enough, the link distance is short enough, and the antenna arrays are wide enough. We will show how nearly full data rate advantage characteristic of MIMO links can be achieved in the presence of free space propagation by means of typical examples.

Figure 1. F-35 Jet Airplane with 12 Element Antenna Array

3. F-35 Jet Airplanes

In this example we assume that two F-35 airplanes are equipped with multi-element slot antenna arrays. As shown in the sketched twelve element array of Figure 1, the slot antenna elements (shown in red) are equally spaced along the front edge of the wings.

The channel matrix is then computed using the locations of the antenna elements on the airplane as shown in Table 1.

Table 1. Location of Antenna Elements on the F-35 (meters)

Element Number	1	2	3	4	5	6	7	8	9	10	11	12
Longitudinal position	-4.55	-3.82	-3.09	-2.36	-1.64	1.89	1.89	-1.64	-2.36	-3.09	-3.82	-4.55
Lateral position	-7.87	-6.61	-5.35	-4.09	-2.83	-1.57	1.57	2.83	4.09	5.35	6.61	7.87

The distance between two elements, m and n, on the two airplanes, respectively, is

$$r_{mn} = \sqrt{\left(d - x_n - x_m\right)^2 + (w - y_n - y_m)^2 + h^2}\ , \tag{1}$$

where d is the longitudinal separation of the two airplanes, travelling oppositely in the longitudinal direction. The longitudinal and lateral locations of each antenna element on the airplane are x_m and y_m , respectively. The lateral and height displacements of the two airplane paths are w and h , respectively. The transmission coefficient between the two elements is

$$T_{mn} = g_m g_n \frac{\exp\left(-jkr_{mn}\right)}{r_{mn}}, \tag{2}$$

where g is the voltage gain of the antenna element in the direction of the corresponding element on the other airplane. We make the approximation that the propagation is truly free space, so that $g_m g_n$ is the same for all m and n ; i.e., we neglect all blockage by airplane structure, etc. Thus, we construct the normalized Channel Coefficient Matrix, $\mathbf{H}$, as

$$H_{mn} = \frac{\dfrac{\exp(-jkr_{mn})}{r_{mn}}}{\sqrt{\mathcal{E}\left[\left|\dfrac{\exp(-jkr_{mn})}{r_{mn}}\right|^2\right]}}, \tag{3}$$

where the expectation, $\mathcal{E}$, is taken over all combinations of m and n . We define the signal to noise ratio, ρ, as that obtained when the total power is radiated from a single element and received by a single element, averaged over all combinations of m and n . Thus the MIMO channel capacity between the two arrays, assuming only the receiver knows the Channel Coefficient Matrix, is given by [1]:†

$$C_{F35} = \log_2\left[\det\left(\mathcal{I}_M + \frac{\rho}{M}\mathbf{H}\mathbf{H}^{\dagger}\right)\right] \text{ bits/sec per Hz,} \tag{4}$$

where M is the number of elements in each of the arrays, $\mathcal{I}_M$ is the identity matrix of dimension M, and $\mathbf{H}^{\dagger}$ is the transpose conjugate of the matrix $\mathbf{H}$. For this study we assume the transmitter uses power control to maintain a constant signal to noise ratio (e.g., $\rho = 10$) as the airplanes approach each other.

For comparison we compute the MIMO capacity of two arrays with the same number of elements in a fully scattered (Rayleigh) environment with the same signal to noise ratio. We average the channel capacity over all instantiations of the scattered propagation. This average channel capacity is called the ergodic Rayleigh capacity, C_R [2]:

$$C_R = M\left\{2\log_2[1+\rho-F] - \frac{F}{\rho\ln 2}\right\} \text{ where } F = 0.25\left(\sqrt{4\rho+1}-1\right)^2. \tag{5}$$

Another type of channel capacity is that which occurs for a Channel Coefficient Matrix having all equal eigenvalues. This type of channel has the maximum capacity, C_E, for a given signal to noise ratio, ρ, and a given number of elements, M [2] .

$$C_E = M\log_2(1+\rho). \tag{6}$$

4. Dependence of Capacity on Distance and Frequency

Using the above formulas we compute the channel capacity as a function of distance and frequency for the F-35 airplanes for two arrays with M = 12. Figure 2, shows for 10 GHz, the dependence of channel capacity on longitudinal separation for the twelve element array case with 100 m lateral and height separation of the parallel flight paths. Note that lateral and height separation prevent the airplanes from approaching nearer than 140 meters. The channel capacity actually exceeds the ergodic Rayleigh capacity mostly out to a longitudinal separation of 400 m..

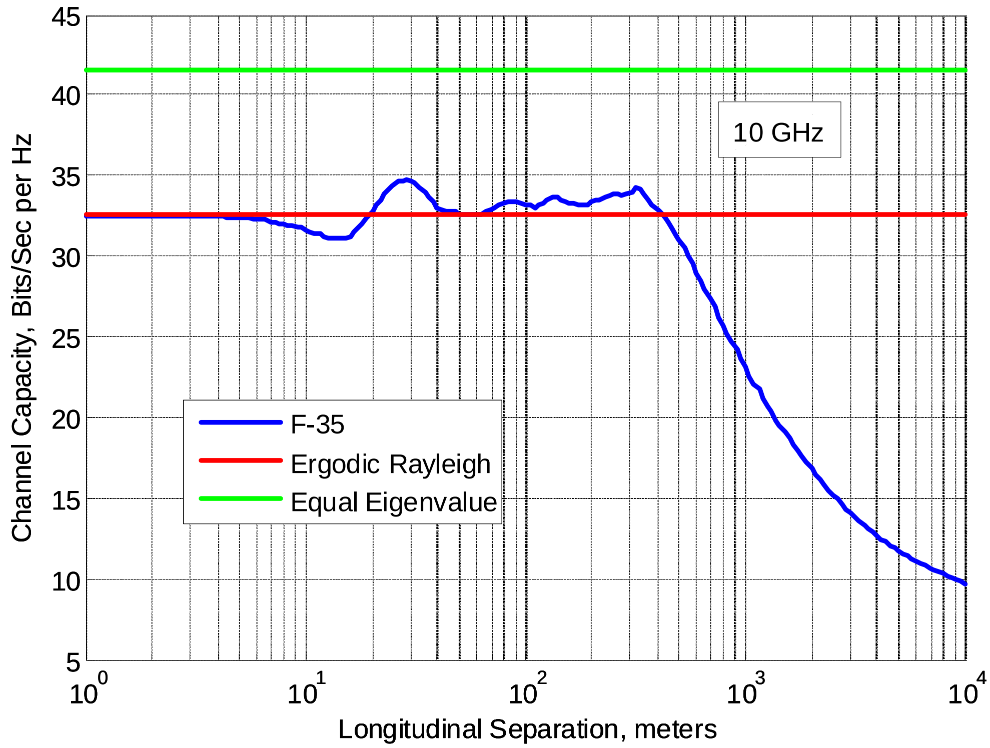

Figure 2. Free Space MIMO Between Two F-35 Jets
12 Element Arrays, 10 dB SNR, 10 GHz
100 m vertical and 100 m lateral displacement

The capacity limit for large longitudinal separation is 6.92 bits/sec per Hz, the keyhole[3] single-input-multiple(12)-output (SIMO) capacity.

Modern jets cruise at about 0.25 km/sec. Two jets approaching each other would remain in the 400 m ergodic Rayleigh MIMO range for about 1.6 seconds at 10 GHz. Of course this oppositely traveling flight pattern is the shortest MIMO duration.

The dependence of channel capacity on longitudinal separation for the case of 120 element arrays on both aircraft was also computed with 100 m vertical and height separation of the flight paths. This dependence is shown for 10 GHz in Figure 3. The MIMO ranges are much the same as for the 12 element array cases but the MIMO Channel capacities are much higher. The MIMO capacity no longer exceeds the ergodic Rayleigh capacity; however, as the radio frequency is increased, the MIMO capacity approaches the ergodic Rayleigh capacity for 120 element arrays.

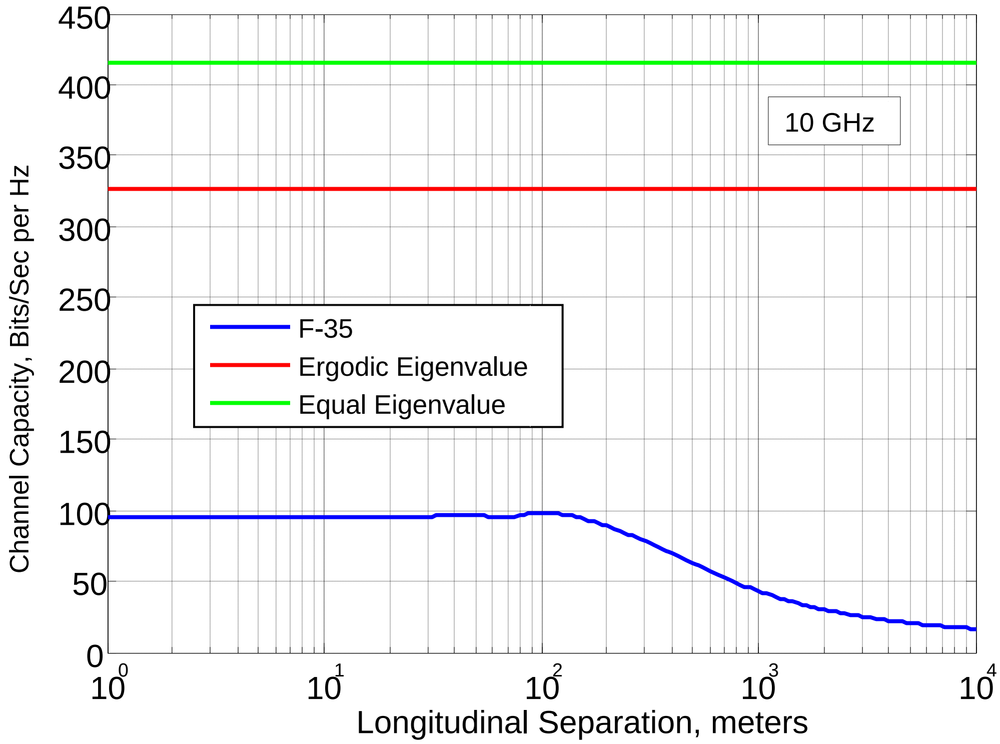

Figure 3. Free Space MIMO Between Two F-35 Jets
120 Element Arrays, 10 dB SNR, 10 GHz
100 m vertical and 100 m lateral displacement

Figure 4. The C-5 Jet Airplane

5. C-5 Jet Airplanes

Another example of jet airplane is the C-5, with a wing span of 222 feet 9 inches as shown in Figure 4. The C-5 again has a cruising speed of 0.25 km/sec. The positions of the the antenna elements for a twelve element array on the wings are given in Table 2.

Table 2. Location of Antenna Elements on the C-5 (meters)

Element Number	1	2	3	4	5	6	7	8	9	10	11	12
Longitudinal position	-9.06	-7.6	-6.13	-4.66	-3.2	-1.73	-1.73	-3.2	-4.66	-6.13	-7.6	-9.06
Lateral position	-15.7	-13.16	-10.62	-8.08	-5.54	-3.0	3.0	5.54	8.08	10.62	13.16	15.7

Using the above formulas we compute the channel capacity as a function of distance and frequency for the C-5 airplanes for two arrays. The dependence of channel capacity on longitudinal separation for the twelve element array case with 100 m vertical and height separation of the flight paths is shown in Figure 5. Note that the channel capacity exceeds the ergodic Rayleigh capacity out to a longitudinal separation of 400 meters for 1 GHz, of 5 km for 10 GHz and of 50 km for 100 GHz. At a cruising speed of 0.25 km/sec in opposite longitudinal directions, the C-5 airplanes remain in 12 element MIMO communications for

1.6 seconds, 20 seconds, and 200 seconds for radio frequencies of 1 GHz, 10 GHz and 100 GHz, respectively.

Figures 5, 6, and 7 show, for 1 GHz, 10 GHz and 100GHz, respectively, the dependence of channel capacity on longitudinal separation of two C-5 jets for the 120 element array case with 100 m vertical and height separation of the flight paths. The MIMO ranges for 120 element arrays are much the same as for the 12 element arrays except the channel capacities are much higher. The 1 GHz, 120 element, channel capacity does not reach ergodic capacity because the 100 m lateral and vertical displacement is too large at that frequency. However the channel capacity remains above 200 bits/sec per Hz out to 200 m longitudinal separation. At cruising speed in opposite longitudinal directions, this implies high data rate MIMO communications for a duration of 0.8 seconds.

At 10 GHz, the 120 element arrays provide ergodic Rayleigh channel capacity (325 bits/sec per Hz) out to a longitudinal separation of 1.5 km, corresponding to 6 seconds duration for oppositely traveling C-5 jets at cruising speed. At 100 GHz radio frequency, ergodic Rayleigh capacity is maintained out to a longitudinal separation of 15 km for a duration of 60 seconds for the same conditions.

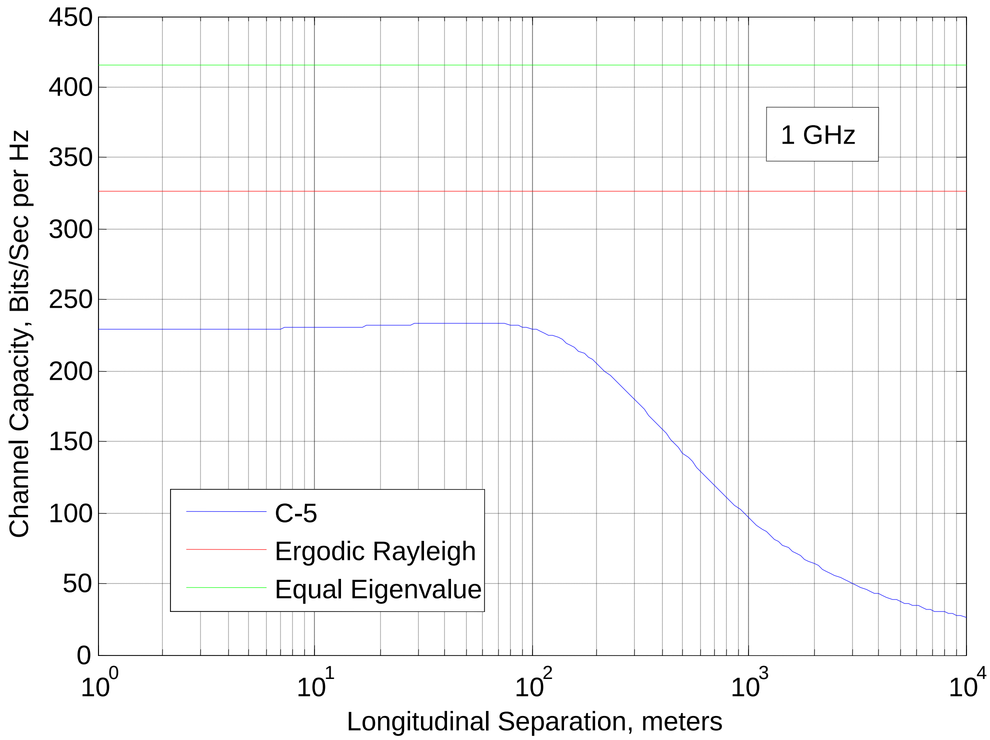

Figure 5. Free Space MIMO Between Two C-5 Jets
120 Element Arrays, 10 SNR, 1 GHz
100 m vertical and 100 m lateral displacement

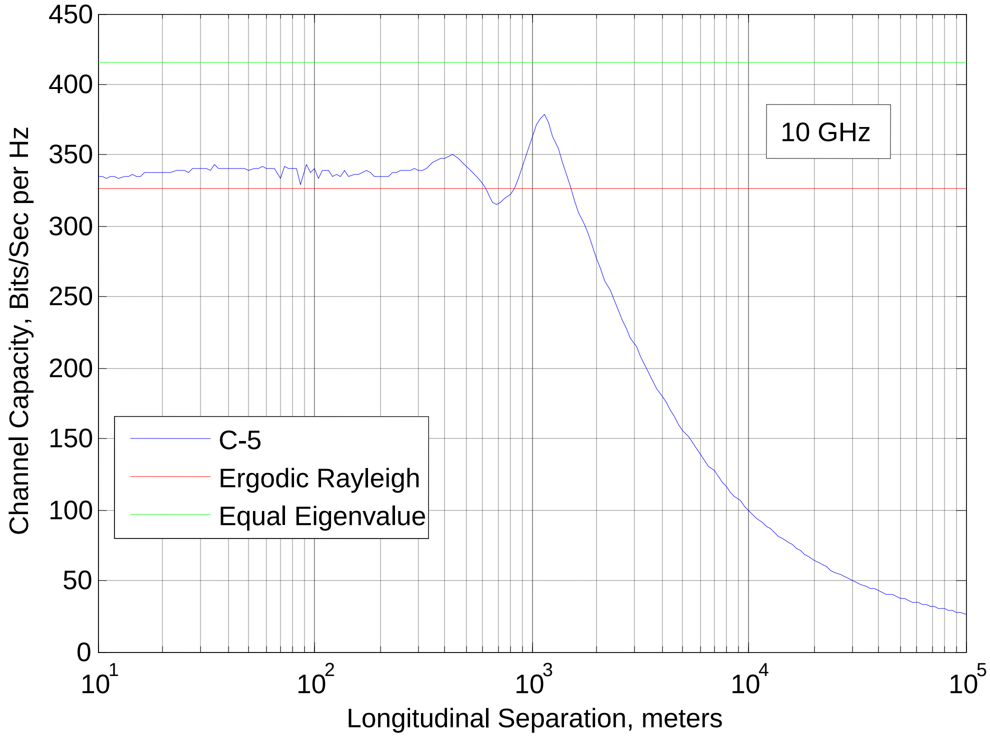

Figure 6. Free Space MIMO Between Two C-5 Jets
120 Element Arrays, 10 dB SNR, 10 GHz
100 m vertical and 100 m lateral displacement

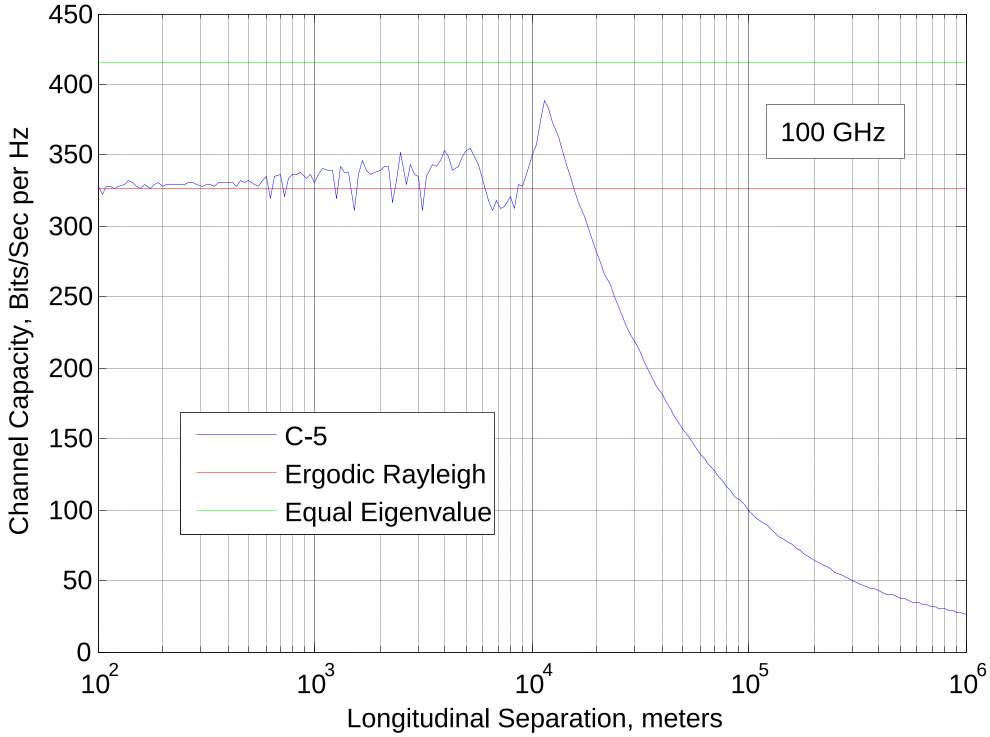

Figure 7. Free Space MIMO Between Two C-5 Jets
120 Element Arrays, 10 dB SNR, 100 GHz
100 m vertical and 100 m lateral displacement

6. Conclusions

If one envisions an 1 MHz bandwidth communication link in free space, a transmitted power of 1 Watt is required to provide 10 dB SNR, ρ_{dB} , at 160 km at 1GHz, 16 km at 10 GHz and 1.6 km at 100 GHz:

$$\rho_{dB} = W_{TdBm} + G_{T\,dB} + G_{R\,dB} - 20\log_{10}\left(4\pi d/\lambda\right) - B_{dB-Hz} - F_{dB} + 174_{dBm/Hz} \quad , \qquad (7)$$

Where d is the distance in meters, λ is the free space wavelength in meters, $G_{TdB} = G_{RdB}$ are the transmit and receive array element gains, respectively, which are about 3 dB, W_{TdBm} is the total transmitted power in decibels above a milliwatt, $B_{dB\text{-}Hz}$ is the bandwidth in dB above 1 Hz, F_{dB} is the receiver noise figure in dB, which we approximate by 3 dB, and 174 is the room temperature thermal noise in dBm/Hz.

For the oppositely traveling aircraft, at 32.5 bits/sec per Hz, a 52 Mbit message could be transmitted in 1.6 seconds (12 element F-35 jet at 10 GHz) and a 650 Mbit in 20 seconds (12 element F-35 at 100 GHz,). For 325 bits/sec per Hz, a 1.95 Gbit message could be transmitted in 6 seconds (120 element C-5 jet at 10 GHz) and a 19.5 Gbit message could be transmitted in 60 seconds (120 element C-5 jet at 100 GHz). At sea level, 100 GHz atmospheric attenuation for dry air is 0.3 dB/km and moist air is 5 dB/km. At aircraft cruising altitudes, we can neglect atmospheric attenuation for the short distances involved. For comparison, a standard 12 cm single sided DVD contains about 38 Gbits of data.

Tactics may allow the communicating aircraft to fly in the same longitudinal direction which, with equalized flight speed, would allow much longer communications while remaining close enough for the large data rates allowed by MIMO communication.

7. References

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," in *Wireless Personal Communications*. Norwood, MA: Kluwer, 1998, vol. 6, pp. 311–335.

[2] M. J. Gans, "Channel capacity between antenna arrays—Part I: Sky noise dominates," in *IEEE Transactions on Communications*, vol. 54, No. 9, September 2006, pp. 1586-1592.

[3] D. Chizhik, G. J. Foschini, M. J. Gans, and R. A. Valenzuela, "Keyholes, correlations and capacities of multielement transmit and receive. Antennas: Correlations and keyholes," *IEEE Trans.Wireless Commun.*, vol. 1, pp. 361–368, Apr. 2002.